20th European White Dwarf Workshop
ASP Conference Series, Vol. 509
Tremblay, Gänsicke, and Marsh, eds.

Heavy Metals Resisting Gravity in White Dwarfs?

Thomas Rauch,[1] Sébastien Gamrath,[2] Pascal Quinet,[2,3] Denny Hoyer,[1] Klaus Werner,[1] and Jeffrey Walter Kruk[4]

[1] *University of Tübingen, Germany;* `rauch@astro.uni-tuebingen.de`

[2] *Université de Mons, Belgium;* `pascal.quinet@umons.ac.be`

[3] *Université de Liège, Belgium*

[4] *NASA Goddard Space Flight Center, Greenbelt, USA*

Abstract. Spectral lines of heavy metals, identified in high-resolution ultraviolet spectra of the DO-type white dwarf RX J0503.9−2854 (RE 0503−289), allow precise abundance determinations of these species by means of advanced non-local thermodynamic equilibrium stellar-atmosphere models – provided that reliable atomic data is available. Such analyses of Zn (atomic number $Z = 30$), Ga (31), Ge (32), As (33), Mo (42), Kr (36), Zr (40), Xe (54), and Ba (56) have recently shown that, without exception, their abundances are unexpectedly strongly supersolar (up to about 5 dex). This is much higher than predicted by recent asymptotic giant branch nucleosynthesis calculations. Thus, the interplay of gravitational settling and radiative levitation may play an important role for their photospheric prominence.

1. Introduction

Werner et al. (2012b) discovered lines of trans-iron elements, namely Ga, Ge, As, Se, Mo, Sn, Te, and I, in the ultraviolet (UV) spectrum of RE 0503−289 (effective temperature $T_{\mathrm{eff}} = 70\,000 \pm 2000$ K, surface gravity $\log(g / \mathrm{cm\,s^{-2}}) = 7.50 \pm 0.1$, Rauch et al. 2016c). Due to the lack of reliable atomic data, they could only determine the Kr and Xe abundances (-4.3 ± 0.5 and -4.2 ± 0.6 in logarithmic mass fractions, respectively). This identification initiated the calculation of transition probabilities for trans-iron elements that allowed then to calculate reliable stellar-atmosphere models. We describe this briefly in Sect. 2. We summarize our results and conclude in Sect. 3.

2. Atomic Data and Stellar-atmosphere Models

State-of-the-art spectral analyses of hot, compact stars that allow deviations from the assumption of a local thermodynamic equilibrium (LTE) require detailed model atoms to represent the respective elements. Reliable transition probabilities are mandatory, not only for lines identified in observed spectra but for the complete model atoms considered in the calculations. Therefore, we computed radiative decay rates, i.e., oscillator strengths and transition probabilities. We used the pseudo-relativistic Hartree-Fock (HFR) method presented by Cowan (1981), modified to take core-polarization effects

Table 1. Ions with newly calculated transition probabilities.

Atom	Ions	Reference
Zn	IV-V	Rauch et al. (2014a)
Ga	IV-VI	Rauch et al. (2015b)
Ge	IV-V	Rauch et al. (2012)
Kr	IV-VII	Rauch et al. (2016c)
Zr	IV-VII	Rauch et al. (2016a)
Mo	IV-VII	Rauch et al. (2016b)
Tc	IV-VI	Werner et al. (2015)
Xe	IV-V, VII	Rauch et al. (2016a)
Ba	V-VII	Rauch et al. (2014b)

(CPOL) into account, giving rise to the HFR+CPOL approach (e.g., Quinet et al. 1999, 2002). Table 1 summarizes our calculations. All calculated oscillator strengths etc. are provided via the registered Tübingen Oscillator Strengths Service (TOSS[1]), that has been developed within the Tübingen project of the German Astrophysical Virtual Observatory (GAVO[2]).

We used the Tübingen NLTE Model Atmosphere Package (TMAP[3], Werner et al. 2003, 2012a) to calculate plane-parallel, chemically homogeneous model atmospheres in hydrostatic and radiative equilibrium. For RE 0503−289, we considered opacities of He, C, N, O, Al, Si, P, S, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, Ga, Ge, As, Kr, Zr, Mo, Sn, and Ba. Model atoms for those elements, not listed in Table 1, were retrieved from the Tübingen Model Atom Database (TMAD[4], Rauch & Deetjen 2003) that has been constructed as part of the Tübingen contribution to GAVO. Theoretical profiles of selected Zr IV, Zr V, and Zr VI lines and an UV observation performed with the Hubble Space Telescope / Space Telescope Imaging Spectrograph (HST/STIS) are compared in Fig. 1. The results of the abundance determinations are shown in Fig. 2

The extreme overabundances of the trans-iron elements were not predicted by stellar models for asymptotic giant branch (AGB) stars (Karakas & Lugaro 2016). It is likely that radiative levitation is working efficiently in RE 0503−289 (Rauch et al. 2016b), increasing abundances by up to about 5 dex compared with solar values (Fig. 3). In the hydrogen-rich DA-type WD G 191−B2 B ($T_{\mathrm{eff}} = 60\,000 \pm 2000\,\mathrm{K}$, $\log g = 7.6 \pm 0.05$, Rauch et al. 2013), that is shown for comparison, this mechanism is acting not that strong (Rauch et al. 2016b).

[1] `http://dc.g-vo.org/TOSS`

[2] `http://www.g-vo.org`

[3] `http://astro.uni-tuebingen.de/~TMAP`

[4] `http://astro.uni-tuebingen.de/~TMAD`

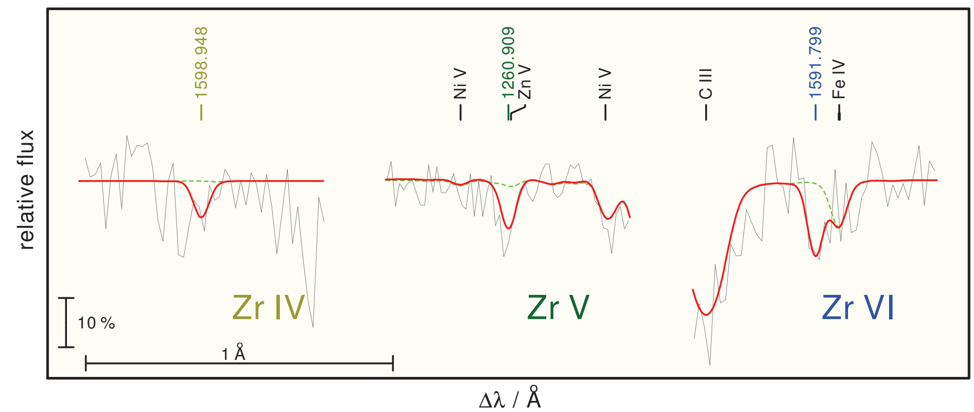

Figure 1. Examples for identified Zr IV, Zr V, and Zr VI lines in the HST/STIS observation of RE 0503−289 compared with our best model. The model (thick, red line) was calculated with an abundance of log Zr = −3.5. The dashed, green spectrum was calculated without Zr. Prominent lines are marked, the Zr lines with their wavelengths from Rauch et al. (2016a).

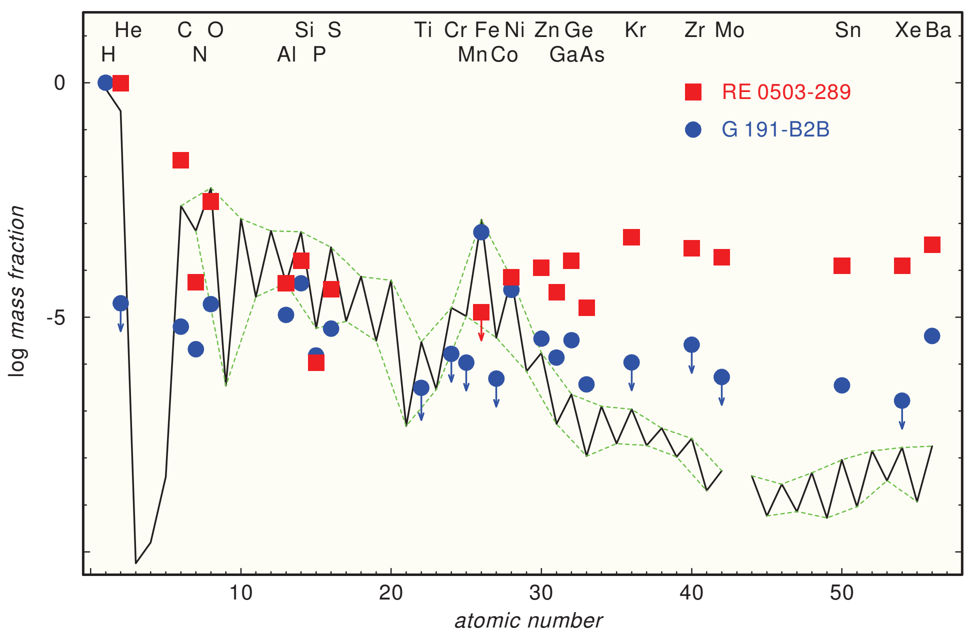

Figure 2. Solar abundances (thick line; the dashed, green lines connect the elements with even and with odd atomic numbers, Asplund et al. 2009, Scott et al. 2015b, Scott et al. 2015a, and Grevesse et al. 2015) compared with the photospheric abundances of G 191−B2 B (blue circles, Rauch et al. 2013) and RE 0503−289 (red squares, Dreizler & Werner 1996, Rauch et al. 2012, Rauch et al. 2014a, Rauch et al. 2014b, Rauch et al. 2015a, Rauch et al. 2015b, Rauch et al. 2016a, Rauch et al. 2016b, Rauch et al. 2016c, and this work). The abundances have uncertainties of about 0.2 dex in general. The arrows indicate upper limits.

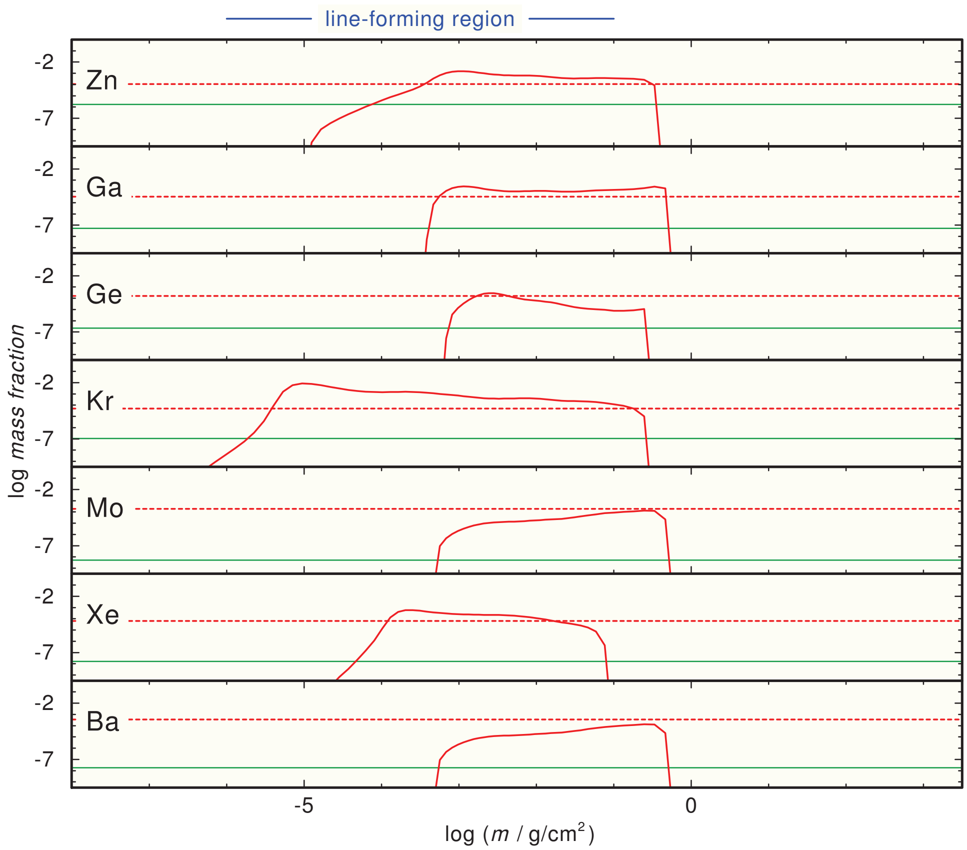

Figure 3. Abundance profiles for selected trans-iron elements (cf., Rauch et al. 2016b) in our diffusion models for RE 0503−289 (thick, red). The red, dashed, horizontal lines indicate the abundances determined from our chemically homogeneous models (Fig. 2). The green, horizontal lines indicate solar abundance values. The formation region of UV lines is indicated at top. *m* is the column mass, measured from the outer boundary of the model atmosphere.

3. Conclusions

The extremely high abundances of trans-iron elements in RE 0503−289 are probably the result of the interplay of radiative levitation and gravitational settling. The diffusion has washed out all information about the previous AGB abundances in this star, preventing to establish constraints for the nucleosynthesis on the AGB.

References

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Cowan, R. D. 1981, The theory of atomic structure and spectra (Berkeley, CA: University of California Press)
Dreizler, S., & Werner, K. 1996, A&A, 314, 217
Grevesse, N., Scott, P., Asplund, M., & Sauval, A. J. 2015, A&A, 573, A27
Karakas, A. I., & Lugaro, M. 2016, ApJ, 825, 26
Quinet, P., Palmeri, P., Biémont, É., et al. 2002, J. Alloys Comp., 344, 255
Quinet, P., Palmeri, P., Biémont, É., et al. 1999, MNRAS, 307, 934
Rauch, T., & Deetjen, J. L. 2003, in Stellar Atmosphere Modeling, Vol. 288, ed. I. Hubeny, D. Mihalas, & K. Werner (San Francisco, CA: ASP), 103
Rauch, T., Gamrath, S., Quinet, P., et al. 2016a, A&A submitted, arXiv:1611.07364
Rauch, T., Hoyer, D., Quinet, P., Gallardo, M., & Raineri, M. 2015a, A&A, 577, A88
Rauch, T., Quinet, P., Hoyer, D., et al. 2016b, A&A, 587, A39
Rauch, T., Quinet, P., Hoyer, D., et al. 2016c, A&A, 590, A128
Rauch, T., Werner, K., Biémont, É., Quinet, P., & Kruk, J. W. 2012, A&A, 546, A55
Rauch, T., Werner, K., Bohlin, R., & Kruk, J. W. 2013, A&A, 560, A106
Rauch, T., Werner, K., Quinet, P., & Kruk, J. W. 2014a, A&A, 564, A41
Rauch, T., Werner, K., Quinet, P., & Kruk, J. W. 2014b, A&A, 566, A10
Rauch, T., Werner, K., Quinet, P., & Kruk, J. W. 2015b, A&A, 577, A6
Scott, P., Asplund, M., Grevesse, N., Bergemann, M., & Sauval, A. J. 2015a, A&A, 573, A26
Scott, P., Grevesse, N., Asplund, M., et al. 2015b, A&A, 573, A25
Werner, K., Deetjen, J. L., Dreizler, S., et al. 2003, in Stellar Atmosphere Modeling, Vol. 288, ed. I. Hubeny, D. Mihalas, & K. Werner (San Francisco, CA: ASP), 31
Werner, K., Dreizler, S., & Rauch, T. 2012a, TMAP: Tübingen NLTE Model-Atmosphere Package, Astrophysics Source Code Library [record ascl:1212.015]
Werner, K., Rauch, T., Kučas, S., & Kruk, J. W. 2015, A&A, 574, A29
Werner, K., Rauch, T., Ringat, E., & Kruk, J. W. 2012b, ApJ, 753, L7